An extremely large-volume, long-runout rock avalanche in the Trans Alai Ranges, Pamir Mountains, Southern Kyrgyzstan.

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Abstract

Massive rock avalanche events form some of the most extensive landslide deposits on Earth and are major geohazards in high-relief mountains. Recent reinterpretation of previously-reported glacial deposits in the Alai Valley of Kyrgyzstan identified a large volume, long-runout rock avalanche deposit in the Komansu River catchment. This deposit likely covers an area ~100 km^2, has a minimum volume of 10 km^3 and a runout of ~28 km. This makes it the longest-runout, and one of the largest-volume, subaerial non-volcanic rock avalanches thus far identified on Earth. The event appears to have occurred 5000-11000 yr B.P., possibly when the region's glaciers were further advanced. It originated in the Trans Alai ranges and we identify a likely source zone within the ranges. Runout appears to have halted when the debris reached the foothills of the Tien Shan at the northern extent of the Alai valley where the deposit ran uphill about 100 m requiring a minimum velocity of 45 m s^{-1}. The rock avalanche was most likely initiated by a large-to-great (M7-M8) earthquake on the range-bounding Main Pamir Thrust, which is known to have sustained similar earthquakes in recent history. The deposit length suggests an apparent coefficient of friction during runout of ~0.11, much smaller than 'normal' apparent coefficient of frictions of >0.6. This may have resulted from partial runout over glacial ice; however the apparent friction is expected empirically for events of this volume even in the absence of ice. Sedimentary evidence for intense basal fragmentation was found suggesting a likely mechanism for the reduced friction coefficient.

Keywords

Rock avalanche; long-runout; dynamic fragmentation; glacial deposits; coefficient of friction

Introduction

Large (>10^6 m^3) rock avalanches with unusually long run-out distances (up to tens of kilometres) occur infrequently in mountain ranges and from volcanic edifices. Rock avalanche deposits have been identified at numerous locations on Earth as well as on Mars and the Moon (e.g. Lucchitta, 1978; Quantin et al., 2004; Lucas and Mangeney, 2007). Their deposits sometimes bear a striking morphometric resemblance to glacial deposits often resulting in misinterpretation: for example, re-examination of deposits in the Karakoram Himalayas by Hewitt (1999) resulted in 15 previously-reported glacial deposits being re-interpreted as rock avalanche deposits. Similar re-interpretations have also occurred elsewhere (e.g. McColl and Davies, 2010; Barth, 2013). Incorrectly identifying rock avalanche deposits as glacial deposits can result in underestimated geohazards risk (McColl and Davies, 2010), whilst also contaminating regional paleoclimate reconstructions vital for understanding of global climate dynamics.

Large rock avalanches are typically characterised by high mobility resulting in unusually small apparent coefficients of friction (=H/L; where H is the total fall height and L is the total travel distance) of <0.6 (Hsü, 1975). Several explanations for this apparent reduction of friction have been proposed including air cushioning (Shreve, 1966), acoustic fluidisation (Melosh, 1979), mechanical fluidisation (Davies, 1982), and lubrication from molten basal layers (Erismann, 1979). However, currently none of these explanations are generally accepted within the scientific community (Davies and McSaveney, 2012). Rock avalanches can be triggered by a number of different factors including strong ground motions during large earthquakes, volcanic eruptions, heavy or long-duration rainfall, rapid snow melt, or a combination of these. In addition, some appear to have no definitive trigger (e.g. Sigurdsson and Williams, 1991; McSaveney, 2002; Hauser, 2002). Identifying the cause of a prehistoric event is therefore difficult; however, analysis of the local and regional environment as well as estimates of the timing of the event can provide some insights. Analysis of the deposit morphology and of the internal structure, if exposed, can offer understanding of the emplacement dynamics.

The intramontane Alai Valley in the Northern Pamir Mountains of Kyrgyzstan (Fig. 1) has numerous large-scale deposits previously interpreted as glacial moraines (e.g. Nikonov et al., 1983; Arrowsmith and Strecker, 1999; Strecker et al., 2003). However, recent analysis by Reznichenko et al. (2013) re-evaluated one of these deposits and determined that in fact it is a rock avalanche deposit. This deposit, on the true right of the Komansu River (Fig. 2), extends north 28 km from the Trans Alai ranges of the Pamir Mountains to the foothills of the Tien Shan Mountains (Fig. 2), making it one of the longest-runout subaerial rock avalanche deposits identified on Earth. Only the distal half of the deposit is exposed at the surface, and this covers an area ~100 km^2 with the proximal section of the deposit missing (Fig. 2).

This study aims to answer specific questions about the Komansu rock avalanche event including the failure mechanism and the dynamic processes involved in the runout of the rock avalanche. This analysis is based on field studies and the interpretation of aerial and satellite images. We also discuss the implications for hazard analysis of such events.

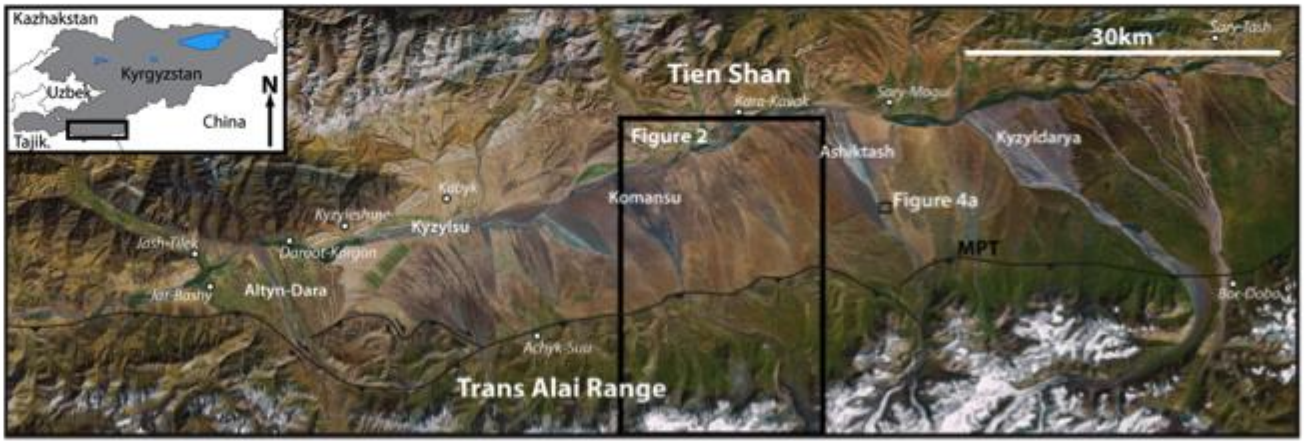

Fig 1 Satellite image of the Alai Valley showing the major towns, rivers, mountain ranges within the region. MPT – Main Pamir Thrust. Boxes indicate areas shown in Figures 2 & 4a

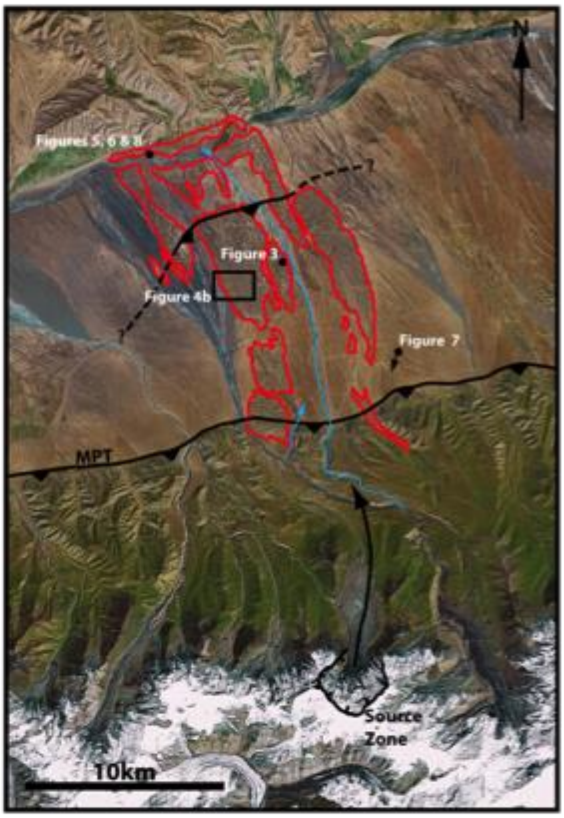

Fig 2 Komansu River catchment showing the exposed Komansu rock avalanche deposit, with probable source headscarp and runout path. Black lines show fault scarps; MPT – Main Pamir Thrust; black

arrow shows likely runout path; red lines show surficial exposure of the deposit; blue lines show the inferred position of the Komansu River immediately after the event (see text); black circles show location of figures. Box indicates area shown in Figure 4b

Regional Setting

Tectonics

The Komansu deposit lies in the centre of the Alai Valley in southern Kyrgyzstan, between the Pamir and Tien Shan Mountains (Fig. 1). The Alai Valley separates the Trans Alai (also known as Zaalai) range of the Northern Pamir from the Tien Shan and was formerly part of a contiguous Cenozoic sedimentary basin, connecting the Tajik depression in the west with the Tarim basin in the east (Strecker et al, 2003). The Trans Alai range, which makes up the southern boundary of the Alai Valley, formed as a result of Eurasian crust being over-thrust by the Pamir block during the late Oligocene-early Miocene (Burtman and Molnar, 1993; Coutand et al., 2002) due to the Indo-Eurasian collision to the south. As a result, the Trans Alai range reach elevations over 7000 m with 3000-3500 m of relief. The range is composed mainly of amalgamated and heavily deformed Paleozoic and Mesozoic terrains while the Alai Valley consists primarily of large Quaternary alluvial fans, moraines, and landslide deposits (Arrowsmith and Strecker, 1999). North of the valley, the Tien Shan rise to over 5000 m with 2000-2500 m relief and is characterised by Devonian limestones and Carboniferous metasediments overlain by Jurrasic conglomerates and sandstones (Strecker et al., 2003).

Present uplift of the Trans Alai range estimated from repeated GPS measurements is 15-30 mm yr^{-1} (Burtman and Molnar, 1993; Arrowsmith and Strecker, 1999) which accounts for between $^{1}/_{3}$ and $^{2}/_{3}$ of the Indo-Eurasian Plate collision deformation at this location. Most of this shortening is thought to occur along the range-bounding Main Pamir Thrust (MPT; Figs. 1 & 2). Arrowsmith and Strecker (1999) estimated that uplift along this fault must be *at least* 6 mm yr^{-1} based on geologic observations while Krumbiegel et al. (2011) estimate a rate of 13 mm yr^{-1} based on geodetic observations. These rapid rates of convergence are supported by the high seismicity along the MPT with several recent major earthquakes along the fault including M7.4 in 1949; M7.3 in 1974 (Zubovich et al, 2009); M6.5 in 1978 (Fan et al, 1994) and M6.7 in 2008 (Zubovich et al, 2009; Krumbiegel et al, 2011).

Quaternary History

Due to the remote location and high elevation relatively limited research has previously been undertaken in the area, resulting in a incomplete Quaternary history. Nevertheless, recent work by

Shatravin (2000) used oxide/protoxide ratios of alluvial and proluvial deposits and proposed that the last maximum glacial extent occurred 30,000 years before present (yr B.P.) with a smaller Holocene re-advance around 8,000 yr B.P. According to Arrowsmith and Strecker (1999) and Shatravin (2000) the period between the Pleistocene glacial maximum and the Holocene re-advance is represented in the geologic record by numerous large landslide deposits. These deposits consist mainly of Neogene sandstones and argillites sourced from the Trans Alai range and typically have a hummocky topography and corresponding arcuate break-off scars (Arrowsmith and Strecker, 1999). Arrowsmith and Strecker (1999) suggested that the largest of these had a runout of 5-6 km from the mountain front.

Geomorphology and Sedimentology

Our re-interpretation of the Komansu deposit as a rock avalanche event is the result of detailed ground investigations including analysis of the geomorphology as well as the sedimentology of the deposit (Reznichenko et al, 2013). Below we provide a brief summary of the evidence for a rock avalanche origin.

Surface Morphology

The Komansu deposit is clearly distinguishable from the surrounding alluvial deposits by its pronounced hummocky terrain (Fig 3). These hummocks are small conical hills, >20 m in height and 50-60 m in diameter (Fig. 3). Arrowsmith and Strecker (1999) described hummocky topography as being present in both glacial and landslide deposits within the Alai Valley, and such hummocks have been identified in other large rock avalanche deposits including those at Socompa, in South America (Wadge et al, 1995) and Fernpass in the European Alps (Prager et al., 2006) amongst others. Hummocky terrain in the rock avalanche deposit from Round Top in New Zealand is thought to have resulted from runout over outwash surface (Dufresne et al., 2010) which would also have occurred during the Komansu event. Nevertheless, hummocks are not definitive evidence of rock avalanches because they can also be characteristic of moraines, and thus Arrowsmith and Strecker (1999) interpreted the Komansu deposit as of glacial origin. However, in the Alai Valley glacial hummocks are typically larger than those of the Komansu deposit and interspersed with kettle-hole deposits formed during glacial melt-out, none of which have been identified in the Komansu deposit (Reznichenko et al, 2013). Figure 4 shows a comparison of the larger, chaotic hummocks of the Ashiktash catchment glacial deposit ~20 km east of the study area and the smaller, more uniform hummocks of the Komansu rock avalanche deposit.

Fig 3 Hummocky terrain of the Komansu deposit. View looking SW (see Fig. 2 for location).

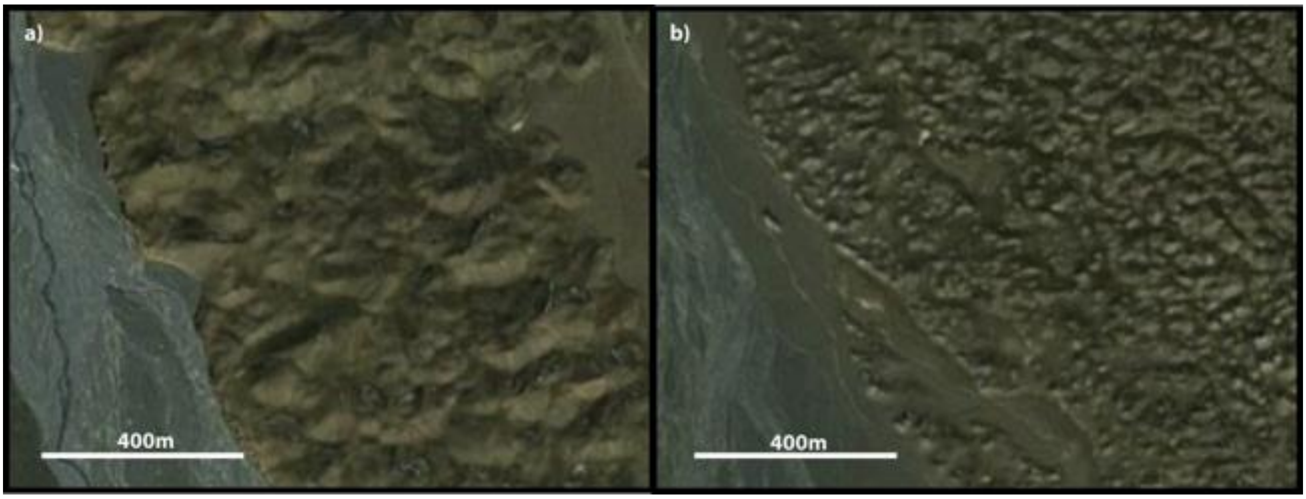

Fig 4 Comparison of hummocks from the a) Ashiktash moraine deposit and b) Komansu rock avalanche deposit. Images from Google Earth.

Sedimentology

Clast counts were undertaken at several locations on the Komansu rock avalanche deposit in order to characterise lithology, clast size and roundness in an attempt to infer its likely origin. The deposit is dominated by angular to very angular and occasionally sub-rounded argillite and quartzite clasts of fine pebble to boulder size, in a matrix of very much finer material. These sediment characteristics correspond to reported descriptions of rock avalanche deposits which comprise a fragmented mass of angular to very angular clasts of the source lithology. Hewitt (1999) used this description to identify 15 rock avalanche deposits in the Karakorum Himalayas previously identified as moraines. The mainly argillite composition of the Komansu deposit agrees with the observation of Arrowsmith and Strecker (1999) of the lithologic composition of several other landslide deposits in the region whose sources are also in the Trans Alai range.

Reznichenko et al. (2012) developed a method to identify sediment of rock avalanche origin by the presence of characteristic micron-scale agglomerates, of widely-graded, largely subangular sub-micron clasts of parent material lithologies as observed under a Scanning Electron Microscope

(SEM). These agglomerates are the result of intense comminution of intact rock and rebonding of the smallest fragments, under rapid, high-stress conditions during rock avalanche runout, and are absent from sediments produced in lower stress and strain-rate glacial processes. Samples from the Komansu deposit were shown by Reznichenko et al. (2013) to contain micron scale agglomerates and hence they deduced a rock avalanche origin, confirming our sedimentologic and morphologic deduction.

Basal Contact

The Kyzylsu River, which runs east-west through the Alai Valley (Fig. 2), has eroded through the distal end of the deposit and exposed a long basal contact (Fig. 5). This sharp unconformity separates the rock avalanche body from the alluvial terrace deposits beneath. At the eastern extent of the outcrop the contact curves upwards before flattening out, thinning the rock avalanche deposit (Fig. 6a). Bedding in the underlying alluvium is clearly truncated against this contact (Fig. 6b) and we interpret this as an ancient Kyzylsu River terrace which was over-ridden and partly preserved by the rock avalanche.

Fig 5 Basal contact between Komansu rock avalanche deposit and alluvial deposits. View looking north (see Fig 2 for location).

Overlying Units

Overlying the rock avalanche deposit is a variable cover of fine-grained loess with thickness from tens of centimetres to several metres. However, most of the loess and characteristic hummocks in the central section of the deposit have been eroded away, corresponding with the location of an abandoned river course (Fig. 2). Here the overlying deposits consist of alluvial sediments similar to those beneath the rock avalanche deposit in figure 5. It is inferred that after the rock avalanche deposit was emplaced, the Komansu River flowed through the centre of the deposit, eroding it and depositing alluvial sediments. Subsequently the river has changed course to its present position on the western flank of the deposit where it incised during uplift along the MPT into its present canyon.

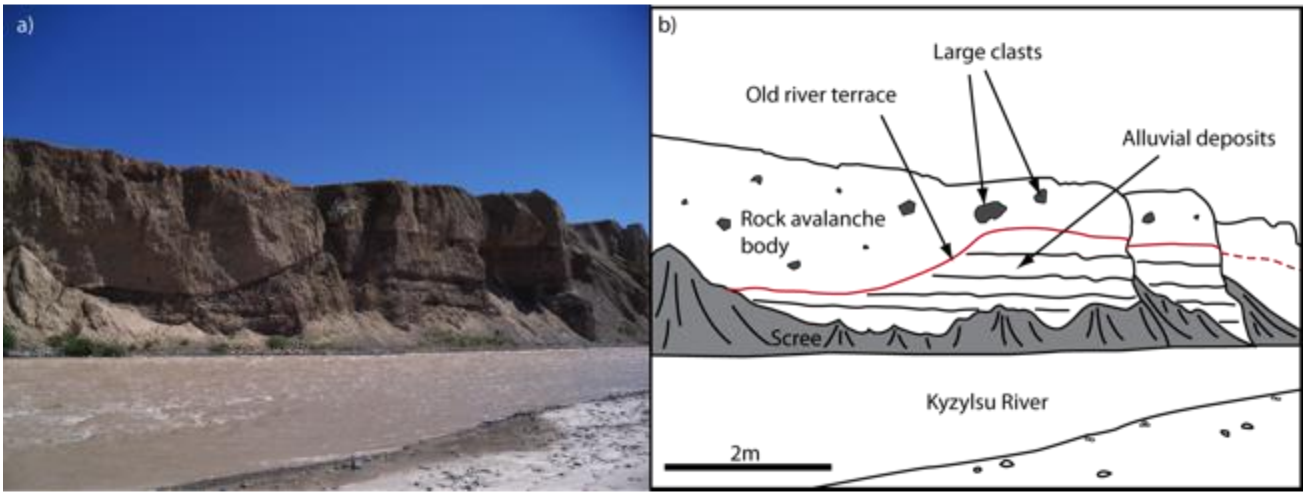

Fig 6 a) View of rock avalanche basal contact with underlying alluvial deposits, looking NE (see Fig 2 for location); b) Interpretation. Red line shows position of basal contact.

<u>Controlling Factors</u>

<u>Source Zone</u>

The location and extent of the Komansu deposit suggest that the rock avalanche has a source zone in the Trans Alai range to the south, rather than from the Tien Shan to the north (Fig. 2). The Trans Alai ranges are >7000 m high, and contain numerous glaciers. As a result we could not definitively identify the source zone. Nevertheless, far-field observation of the mountain range combined with satellite images and field mapping allowed us to identify a probable source zone (Figs. 2 & 7). This source zone shows the arcuate bowl shape typical of a large rock avalanche source (Turnbull & Davies, 2006), a sufficiently large size to yield the apparent volume of the deposit, and is suitably orientated to generate a landslide deposit in the same location as the current Komansu rock avalanche deposit (Fig. 2).

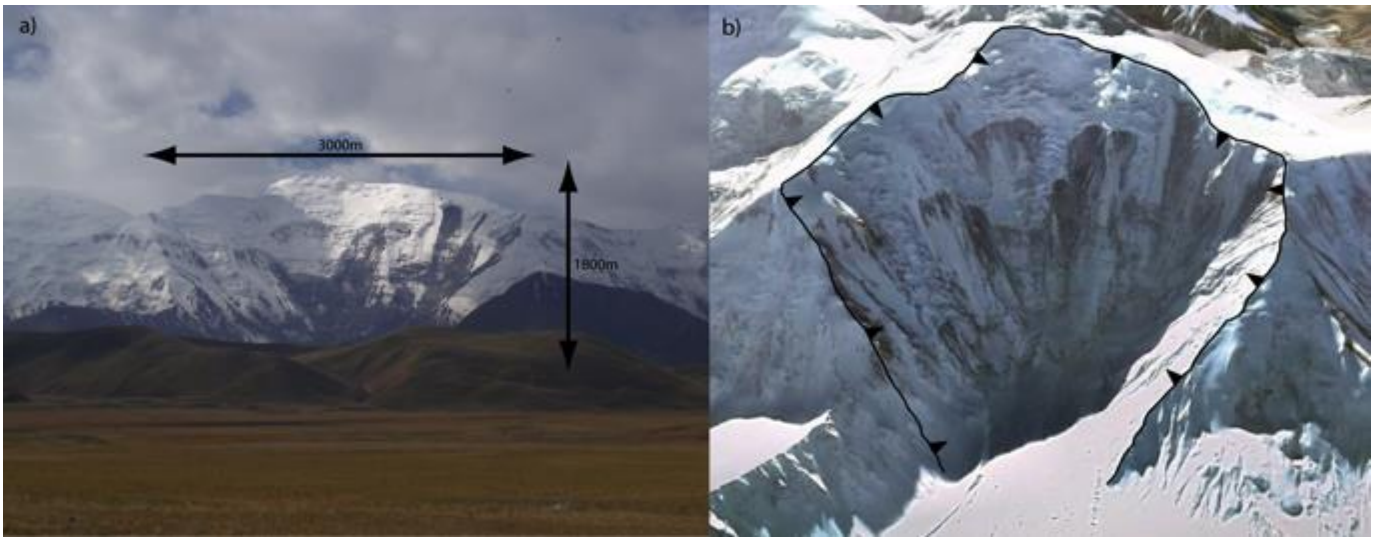

Fig 7 a) Photograph looking SW at the probable source zone for the Komansu rock avalanche deposit with dimensions (see Fig 2 for location); b) Google Earth image (looking SE) of the probable source zone showing the detachment scar. Another large scar 8 km farther east is less well situated with respect to the deposit so was discounted.

Timing

Arrowsmith and Strecker (1999) suggested that the majority of landslide deposits they identified in the region date to between the Late Pleistocene and Holocene. We identify circumstantial evidence which suggests that the Komansu rock avalanche also corresponds to this time with an age of at least several thousand years.

The rock avalanche deposit itself has two continuous thrust fault scarps of the MPT running through it (Fig. 2) with 30 m high surface displacements. These scarps represent multiple surface ruptures of the MPT through the deposit since it was emplaced. On major faults such as the MPT, recurrence intervals between major earthquakes are *at least* several hundred years (e.g. Lienkaemper et al. 2012) which suggests a deposit age of several thousand years is required. Using the estimated slip rates along the MPT suggests an age of 2,300-5,000 years. Nonetheless, field mapping during this study identified a new trace of the MPT with tens of metres of slip at the surface, 10 km north of the main MPT trace (Fig. 2). Two traces of the fault requires the 2,300-5,000 year ages to be doubled to ~5 to 11 ka if the two traces of the fault both accommodate regional deformation.

The lack of surficial exposure of the deposit in its proximal section has two possible explanations relevant to the timing of the event. Either the rock avalanche travelled across a glacier, or it was subsequently eroded or buried by fluvio-glacial deposits. For the rock avalanche to have travelled the first ~15 km of its runout along glacial ice requires it to have occurred at a time when the glaciers were substantially more advanced than at present. Despite the suggested age for the deposit being considerably after the last glacial maximum, the upper age estimate corresponds to a time when the regions glaciers were likely to still be more advanced than today. However, if the deposit age corresponds to the lower estimate then the region’s glaciers are likely to have substantially retreated, suggesting runout over glacial ice was minimal. Analysis of the deposit age alone is insufficient to determine whether or not runout over glacial ice occurred however, inspection of the excessive runout length may provide some insight.

Runout Length

Large rock avalanches have apparent coefficient of frictions <0.6, lower than those of smaller (<10^6m^3) rock avalanches (Hsü, 1975). This reduced coefficient of friction has been correlated with the ratio of excessive runout length to fall height. Hsü (1975) proposed the relationship:

$$L_e = L - H \,/\, \tan 32 \qquad (1)$$

where L_e is the excess travel distance, L is the actual travel distance, H is the fall height, and $\tan 32$ represents the 'normal' coefficient of friction of rock on rock (Byerlee, 1978). Applying equation 1 shows that the length of the Komansu deposit was five to six times longer than expected for an event with normal friction (Table 1). Another measure of excessive runout length, *fahrböschung*, which measures the angle between the maximum elevation of the pre-event source and the distal extent of debris, is just 6.1° and is similar to other massive rock avalanche events (Table 2).

Parameter	**Value**
Debris volume, $\boldsymbol{V}$ (m^3)	10^{10}
Final deposit elevation (m)	2,800
Source zone elevation (m)	5,800
Fall height, $\boldsymbol{H}$ (m)	3,000
Runout length, $\boldsymbol{L}$ (m)	28,000
Excessive runout length, $\boldsymbol{L_e}$ (m)	23,199
Apparent coefficient of friction	0.11
Fahrböschung	6.1°

Table 1 Runout parameters of the Komansu rock avalanche.

The excessive runout of the Komansu rock avalanche is emphasised by the fact that for the latter half of its runout length, after it entered the Alai Valley, it appears to have been unconfined. Nicoletti and Sorriso-Valvo (1996) analysed 40 rock avalanche deposits in an attempt to find the extent to which local morphology controls the motion and shape of such events. They distinguished 3 ways in which morphology affected motion: a) channeling; b) unconfined spreading; and c) right-angle impact of the debris with mobility reducing from a to c. Nicoletti and Sorriso-Valvo (1996) established equations to forecast maximum runout lengths in each case for a given volume:

$$\text{a) } L = -11.1 + 23.6 \log V \qquad (2)$$

$$\text{b) } L = -1.22 + 4.66 \log V \qquad (3)$$

$$\text{c) } L = -4.38 + 5.11 \log V \qquad (4)$$

where L is in kilometres and V is in millions of km^3. Given the Komansu rock avalanche runout was confined during the first half of its runout and unconfined in the latter half, a maximum runout of between 83 km and 17 km is expected. Similarly Davies (1982) used empirical data to estimate runout lengths compared to volume and found:

$$L = 9.98\,V^{0.32} \tag{5}$$

with $r^2 = 0.92$. This suggests an expected runout of >15 km for >10 km^3 volume. Runout over glacial ice is therefore not required to explain the long runout of the Komansu rock avalanche.

Runout Velocity

The deposit is present on both banks of the Kyzylsu River (Fig. 2) and appears to have moved uphill as it reached the opposing slope of the Tien Shan. The distal end the deposit is *at least* 100 m higher than its lowest point on the true left bank of the Kyzylsu River. If we assume that the kinetic energy of the rock avalanche was converted completely to gravitational potential energy as it ran uphill upon reaching the Tien Shan, we find the rock avalanche must have been travelling *at least* 45 m s^{-1} (~160 km hr^{-1}) when it reached the Tien Shan. This is a *minimum* estimate of its velocity assuming that all kinetic energy was transferred to potential energy. In reality much of the kinetic energy will be lost to friction, heat, sound etc. A rock avalanche travelling at this velocity, unimpeded, would likely continue to runout for many additional kilometres.

Runout Mechanism

Close inspection of the basal contact in figures 5 and 6 shows that a thin (~10 cm) layer of very fine-grained material separates the rock avalanche deposit from the alluvial deposits (Fig. 8). This material has a consistent fine-sand-to-clay size distribution and distinct upper and lower boundaries (Fig. 8). The ~10 m thick rock avalanche unit above contains large (up to boulder size), angular clasts supported in a fine (up to coarse sand size) matrix. The cause of this stratification of the rock avalanche deposit is likely the result of high normal and shear stresses in the basal region resulting in concentrated comminution of rock debris in this area (Davies et al., 2010).

Similar stratification has been identified in the Socompa volcanic debris avalanche deposit in Chile (Le Corvec, 2005) which occurred 7,200 yr B.P., had a total volume of 36 km^3 (only ~25 km^3 was involved in the runout however, with the rest remaining proximal to the volcano), and a runout of 40 km (Wadge et al. 1995; Van Wyk de Vries et al., 2001). The Socompa event formed a heavily fragmented lower unit containing thin internal shear bands and an overlying, less fragmented breccia deposit (Wadge et al. 1995; Le Corvec, 2005). Furthermore, the Socompa deposit also has prominent non-striated hummocky topography and an average thickness on the order of 40 m (Davies et al., 2010) and therefore bears notable similarities to the Komansu deposit.

The Socompa event was modelled numerically first by Kelfoun and Druitt (2005) using a constant basal shear resistance, then by Davies et al. (2010) who found that the deposit morphology could be sufficiently replicated in the model by applying a basal resistance factor derived from theoretical analysis of rock fragmentation. This provides a mechanical explanation for the small apparent coefficient of friction and the excessive runout lengths of both the Socompa and Komansu events. Davies (1982) estimated the apparent coefficient of friction for various debris volumes from available empirical data; for a deposit with a volume of 10 km^3 the expected apparent coefficient of friction was 0.11. We estimate that the Komansu deposit contains a volume of *at least* 10 km^3 and have shown that the apparent coefficient of friction for the event was ~0.11 (Table 1). Wadge et al. (1995) similarly estimated that the Socompa event had a coefficient of friction of 0.07-0.14.

The process of dynamic rock fragmentation proposed by Davies et al. (2010) provides a plausible mechanism for the occurrence of this value of basal shear resistance. This suggests that when fragmentation is confined to a basal layer, explosive failure of rock particles exerts a pressure on the overlying material, supporting its weight and reducing the basal effective stress, resistance and thus the apparent coefficient of friction. This mechanism is therefore able to explain the presence of a highly fragmented basal unit, an overlying less fragmented unit, and the reduced basal shear resistance noted in both the Socompa debris avalanche deposit and the Komansu deposit.

A final factor that may have influenced the excessive runout is if part of the runout lay over glacial ice. This factor is accepted as typically enhancing runout with a basal friction coefficient of 0.1 (e.g. McSaveney, 1978; Eisbacher, 1979; Evans and Clague, 1988). Such a coefficient corresponds to our calculated value for the Komansu deposit (Table 1) and, combined with the lack of proximal deposit exposure, suggests the possibility that the rock avalanche at least partially ran out across glacier. Howevr, given that the deposit length is similar to other events of this magnitude (Table 2), it is not necessary to infer supraglacial runout.

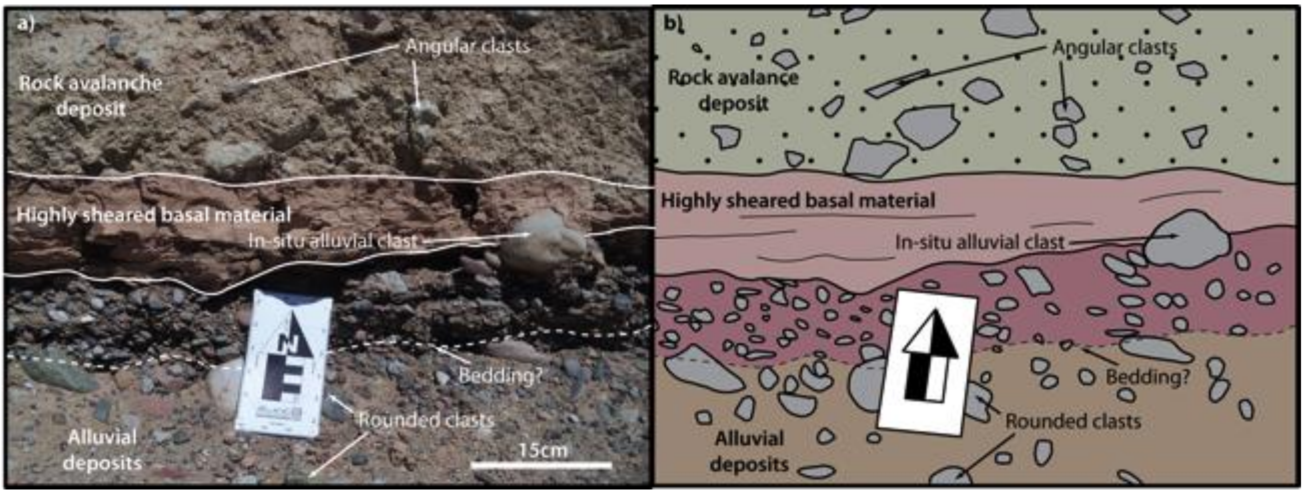

Fig 8 Interpreted photo (a) and sketch (b) of basal contact between rock avalanche deposit and alluvial deposits. Note the highly sheared material at the base of the rock avalanche deposit which has flowed over the alluvial deposits without moving the large clast at the right of the image. This suggests relatively low basal shear stress as required by the long runout.

<u>Discussion</u>

<u>Size and Runout Length</u>

The Komansu rock avalanche deposit has a maximum straight line distance between the source zone and distal end of ~26 km although we estimate a likely curvilinear runout path of ~28 km (Fig. 2). Maximum width of the deposit is ~11 km; the exposed deposit has a fairly uniform width (Fig. 2). The total exposed deposit covers an area ~120 km^2 although accounting for the non-exposed deposit suggests it could cover a total area of >250 km^2. Only a single exposure containing a cross-sectional profile of the deposit has thus far been identified, located at the distal end of the deposit (Figs. 5 & 6). This exposure shows a total deposit thickness of ~10 m and the upper contact has no evidence of erosion. Without further cross-sectional exposures it is difficult to estimate whether this thickness represents a likely maximum or minimum. We note however, for the Socompa rock avalanche the deposit thickness varies between 40 m and 90 m (Wadge et al., 1995) while the (valley-confined) Flims rock avalanche varies greatly, up to a maximum of 500 m (Pollet and Schneider, 2004). We also note that the characteristic hummocks of the Komansu deposit are up to 40 m or more in height suggesting much greater thickness than that visible in outcrop. It therefore seems likely that ~10 m is a minimum thickness and the average is likely to be considerably larger than this. Thus we estimate the Komansu rock avalanche involved a volume of *at least* 10 km^3, and probably considerably more.
Our minimum estimates suggest that the Komansu rock avalanche is one of the largest subaerial rock avalanches currently identified on Earth. Its estimated volume is comparable to that of the notable Flims rock avalanche in Austria (Pollet and Schneider, 2004) and the Tsergo Ri rock avalanche in

Nepal (Schramm et al., 1998; Ibetsberger, 1996) (Table 2). However, depending on its true thickness, the Komansu rock avalanche may in fact be appreciably larger than both. Only the Bogd Fault event in Mongolia at 50 km^3 (Philip and Ritz, 1999), the Saidmarreh event in Iran at 45 km^3 (Roberts and Evans, 2013), and the Socompa event in Chile at 36 km^3 (Wadge et al., 1995) contain larger volumes (Table 2). At 28 km the Komansu runout length is second only to the 40 km runout Socompa event, being far larger than the 19 km Saidmarreh and 20 km Bogd Fault events despite both having larger volumes (Table 2). However, the Socompa event was a volcanic debris avalanche, and these generally appear to involve larger volumes and higher mobility's than non-volcanic rock avalanches (Dade and Huppert, 1998). Thus the Komansu event represents the largest identified runout, and likely the third largest volume, of a subaerial, non-volcanic rock avalanche on Earth.

Rock Avalanche	**Volume (km^3)**	**Runout length (km)**	**Friction coefficient**
Bogd Fault (Mongolia)	50	20	0.05
Saidmerrah (Iran)	45	19	0.04
Socompa (Chile)[a]	36	40	0.07-0.14
Flims (Austria)	12	16.5	0.12
Komansu (Kyrgyzstan)	>10	28	0.11
Tsergo Ri (Nepal)	10	~12	~0.22
Fernpass (Austria)	1	10.8 & 15.5[b]	0.11 & 0.09[b]

Table 2 – Comparison of the largest subaerial rock avalanches from around the world. See text for references. [a]Volcanic debris avalanche. [b]During runout the Fernpass rock avalanche split into two branches with different runout lengths and associated friction coefficients.

Initiation

Establishing the trigger for an ancient event such as the Komansu rock avalanche is difficult and requires a number of assumptions. Nevertheless, a most likely cause can be arrived at by a process of elimination. This region is especially arid and has likely been so for the majority of the Quaternary period (e.g. Abramowski et al., 2006), making heavy or long-duration precipitation unlikely. Furthermore, such rainstorm events rarely result in large, deep-seated rock slope failures such as that required for the Komansu event, thus we do not consider this a likely cause. Similarly, rapid snow melt and permafrost degradation are unlikely to result in deep-seated failures. The most likely trigger is therefore strong ground motions during a large local earthquake. The MPT has been the main source of tectonic uplift in this region for several million years and was certainly active at the time of the Komansu rock avalanche. Importantly there are MPT fault scarps up to ~30 m high running through the deposit that represent multiple ruptures along the MPT in the area since the rock avalanche was deposited (Arrowsmith and Stecker, 1999). Furthermore, the MPT is known to be capable of generating large-to-great (M7-8) earthquakes and is sufficiently close to the Trans Alai ranges to generate high intensity shaking in the source region, with substantial topographic amplification in the upper parts of the range (Buech et al., 2010). Historically, large earthquakes are known to have caused sizeable rock avalanches with excessive runouts. The Bogd Fault, Saidmarreh, and Tsergo Ri events are all inferred to have seismic triggers associated with nearby major fault systems (Phillip and Ritz, 1999; Roberts and Evans, 2013; Weidinger et al., 1996). It therefore seems most likely that the Komansu rock avalanche was initiated by a large-to-great (M7-M8) earthquake occurring on the MPT in the central Alai Valley.

Hazard Analysis

The identification of the Komansu rock avalanche presents several important issues for future hazard analysis. Firstly, the re-interpretation of this deposit as a rock avalanche deposit rather than a glacial deposit, combined with several other notable examples globally, suggests that massive landslides are more common than previously thought. Further assessment of other 'glacial deposits' within the Alai Valley is required in order to understand how frequently such events occur in this region. Continued global assessment of deposits such as the Komansu deposit are likely to yield further examples of this misinterpretation. Thus mountainous areas with glacial deposits, particularly those coincident with active faults, are likely to have a much higher rock avalanche hazard than currently believed.

The mechanism(s) involved in the excessive runout length are also important. Most towns and villages within the Alai Valley are situated at its northern extent, at the base of the Tien Shan (Fig 1). Prior to identification of the Komansu rock avalanche, the major mass movement hazard posed to these towns and villages was that from the Tien Shan. However, the Komansu rock avalanche suggests that these locations have always had the additional threat of long runout rock avalanches originating in the Trans Alai. Our work demonstrates that the small apparent coefficient of friction that resulted in the large runout length was the result of either runout over glacial ice, or of dynamic fragmentation of rock material in the basal region, or a combination of these. If runout over glacial ice was necessary to explain the deposit extent then the retreat of glaciers in the region would suggest that a recurrence of a similar event is unlikely as future events would have only limited runout length over ice. However, since the runout appears to be satisfactorily explained by dynamic fragmentation, and there is evidence that this process occurred, then a long runout rock avalanche could occur at any time as the only pre-requisite is the failure of a large enough volume of material. Given the potential for a large-magnitude earthquake in the region, the occurrence of a future large-volume rock avalanche with similar runout characteristics cannot be discounted. Conclusively establishing the dominant mechanism involved during runout is therefore vital to better understanding these events and the hazard they pose.

Conclusions

Reanalysis of a deposit in the central Alai Valley in southern Kyrgyzstan that was previously thought to be of glacial origin demonstrates that it is instead a massive coseismic rock avalanche deposit. This deposit, on the true right of the Komansu River, covers an area >250 km^2, contains a volume of at least 10 km^3 and probably considerably more, and has a total runout length of ~28 km. It is thus the longest-runout, and one of the largest-volume, subaerial, non-volcanic rock avalanches thus far identified on Earth. Runout of the debris was halted when it reached the lower slopes of the Tien Shan at the northern boundary of the Alai Valley. Here the debris ran uphill for up to 100 m suggesting it was travelling *at least* 45 ms^{-1} before it stopped. The event appears to have occurred at least 5,000-11,000 years ago, possibly during a time when the regions glaciers were further advanced. The most likely cause was a large-to-great (M7-M8) earthquake centred on the range-bounding Main Pamir Thrust. This fault has a fast slip-rate and is known to have produced earthquakes of this size in recent history. The runout length corresponds to an apparent coefficient of friction of ~0.11, consistent with other events of this size which have not involved runout over ice. This small apparent coefficient of friction may be the result of partial runout over glacial ice; dynamic fragmentation of a thin basal layer; or a combination of both. Runout over glacial ice has been shown to typically result in basal friction coefficients of 0.1, while dynamic fragmentation explains both the observed internal structure of the Komansu deposit and its long runout. Thus the presence of advanced glaciers is not necessary to explain the deposit extent, and such events could recur in the future. Additional mapping, field investigations, and analysis of other glacial landforms in active mountain belts worldwide may assist with the discovery of other large-runout rock avalanches and hazard assessments.

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